International Journal of Mechanical and Production Engineering Research and Development (IJMPERD)
ISSN(P): 2249-6890; ISSN(E): 2249-8001
Vol. 9, Issue 3, Jun 2019, 1309-1322

A REVIEW OF CFD INVESTIGATIONS ON HEAT TRANSFER AUGMENTATION OF FORCED CONVECTION SOLAR AIR HEATER THROUGH ENHANCED FLUID TURBULENCE LEVELS

M. S. MANJUNATH[1] & MADHWESH. N[2*]

[1]*Faculty, School of Engineering and IT, Manipal Academy of Higher Education, Dubai Campus, Dubai, UAE*

[2]*Faculty, Department of Mechanical and Manufacturing Engineering, Manipal Institute of Technology, Academy of Higher Education, Manipal, India*

ABSTRACT

Solar air heaters generally exhibit lower levels of thermal performance due to higher heat losses and poor heat transfer characteristics of air which is the working fluid. Many investigations, both experimental and numerical, have been carried out in the past to overcome these limitations. One of the commonly used techniques for thermal performance enhancement in solar air heaters is to enhance the turbulence levels in the flowing air stream. This paper presents a detailed review of investigations involving numerical studies for thermal performance enhancement of solar air heater by enhancing turbulence levels in the air flow. It is observed that the focus of numerical simulation studies has been on the use of artificial roughness elements, corrugations and vortex generators to achieve higher turbulence levels in the air flow. RNG k-e turbulence model has been commonly used to capture the turbulent flow characteristics. An attempt has also been made to summarize the operating parameters and heat transfer enhancement parameters of various numerical simulation studies done in the past with respect to turbulence enhancement technique.

KEYWORDS: CFD, Solar Air Heater, Efficiency, Turbulator, Artificial Roughness & Turbulent Intensity

Received: Apr 12, 2019; **Accepted:** May 02, 2019; **Published:** May 31, 2019; **Paper Id.:** IJMPERDJUN2019137

1. INTRODUCTION

1.1 Need For Performance Enhancement of Solar Air Heater

Flat plate solar air heaters have been commonly used for various applications such as space heating, food industries for drying of spices, tea, coffee, fish, paddy etc., drying of timber and cooling of photovoltaic panels to improve its efficiency while simultaneously generating hot air for space heating applications. Flat plate solar air heaters have a simple design and are easy to operate which leads to low cost maintenance. However, they have higher thermal losses and the working fluid which is air, further adds to the performance issues as it is characterized by poor heat transfer capabilities. As a result, flat plate solar air heaters operate at lower levels of thermal efficiency. Hence, there have been lot of efforts in the past to provide improvements in order to enhance the thermal efficiency.

1.2 Role of CFD in Performance Enhancement

The most widely used technique for performance enhancement of solar air heaters has been to increase the fluid turbulence levels, thereby enhancing the fluid mixing leading to enhanced heat transfer between the absorber plate and fluid. Both experimental as well as numerical investigations using Computational Fluid Dynamics (CFD)

have been reported in the past. Experimental investigations involving fluid flow and heat transfer are typically time consuming and require recurring investments to set up and operate the test rigs. The biggest limitation of experimental methodology is that the fluid flow patterns cannot be visualized unless some flow visualization systems are made use of which are expensive. However, understanding of the fluid flow patterns greatly helps the engineers to predict the flow behaviour which leads to the development of efficient flow systems. Computational Fluid Dynamics (CFD) is a numerical methodology which offers a wide range of fluid flow and heat transfer simulations and has been very commonly used by various researchers to develop improved fluid and thermal systems such as solar air heaters. The advent of advanced computer workstations in the last few years has greatly enabled the researchers to apply CFD to seek solutions for engineering problems. In order to determine the effect of varying operating and design parameters on the overall thermal performance of solar air heater, the CFD offers an economical and relatively faster solution process. Most importantly, CFD offers flow visualization which helps significantly to predict the flow behaviour and provide design improvements in solar air heaters. The CFD basically involves simplification of governing partial differential equations of fluid flow and heat transfer into a set of linear simultaneous equations which are then solved using matrix solution methodologies. A typical CFD analysis of a solar air heater system involves the following steps.

- Selection of computational domain
- Discretization of computational domain/Meshing
- Selection of governing equations
- Specification of boundary conditions and numerical schemes
- Grid independence study
- Validation of CFD results

This paper presents a detailed review of CFD studies on thermal performance improvement of forced convection solar air heaters by using turbulence enhancement methods.

2. TURBULENCE ENHANCEMENT STUDIES USING CFD

2.1 Investigations on Transverse Ribs

The effect of design parameters of the ribs such as the rib geometry, pitch and rib height have been widely studied and optimized both experimentally and numerically. Yadav and Bhagoria (2014) evaluated the thermal performance enhancement in the presence of square ribs as shown in Figure 1in terms of Nusselt number enhancement and thermal enhancement factor. They made use of 12 configurations of ribs by varying the rib pitch and height on the absorber plate. The pitch was varied as 10, 15, 20 and 25 mm which corresponds to the normalized pitch value of 14.29, 21.43, 28.57 and 35.71 respectively. The rib height was varied as 0.7, 1.0 and 1.4 mm which corresponds to the normalized height of 0.021, 0.03 and 0.042 respectively. In order to capture the turbulent flow characteristics and its influence on the flow and heat transfer, they made use of RNG k-e turbulence model after careful evaluation of all turbulence models provided in Ansys Fluent software tool. The results showed that the maximum Nusselt number enhancement was about 2.86 times higher relative to the smooth duct while the fiction factor enhancement was about 3.84 times for the relative pitch of 7.14 and relative rib height of 0.042 for the flow Reynolds number of 15,000. The CFD results also revealed that the peak values of the Nusselt number occur in the inter-rib region which is coincident with locations of flow reattachment. The thermal

enhancement factor was found to vary between 1.22-1.88. In another study, Yadav and Bhagoria (2015) investigated the effectiveness of transverse square sectioned ribs on the absorber plate for the flow Reynolds number range of 3800 to 18,000. The relative roughness pitch was varied from 7.14 to 17.86 and the rib height was fixed at 1.4 mm. The analysis was carried using the Ansys Fluent 12.1 software tool. The results were validated against the experimental results of Ahn (2001) as shown in Figure 2 and were found to have a close match with a maximum deviation of about ±10%. The maximum enhancement in thermal enhancement factor was found to be about 1.82 for the flow Reynolds number of 18,000. The transverse square ribs were further modified to have square wave profile as shown in Figure 3(Singh and Singh, 2018) where the effect of varying relative roughness pitch for a fixed relative rib height of 0.043 was studied. The normalized picth was varied as 4, 10, 16, 24 and 30. The CFD results reveal that the presence of wavy profile facilitates the reduction of recirculation zones in the inter-rib regions thereby increasing the flow reattachment length and hence the heat transfer from the absorber plate.

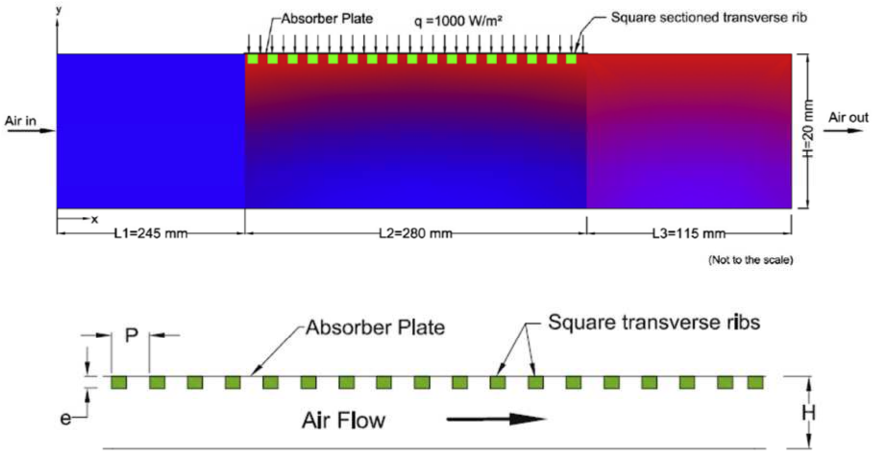

Figure 1: Computational Domain of Air Duct with Square Sectioned Transverse Ribs (Yadav and Bhagoria, 2014)

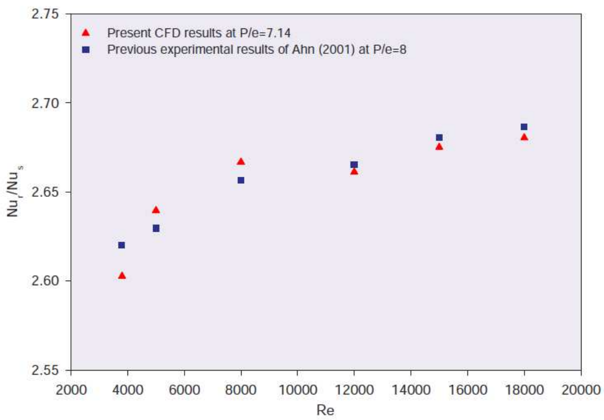

Figure 2: Experimerntal Validation of CFD Results (Ahn, 2001)

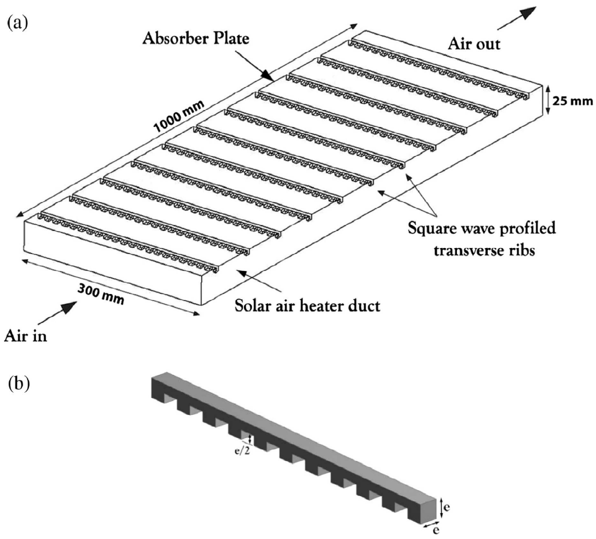

Figure 3: (a) Square Wave Profiled Transverse Rib on Absorber Plate (b) Square Wave Profiled Rib Geometry (Singh and Singh, 2018)

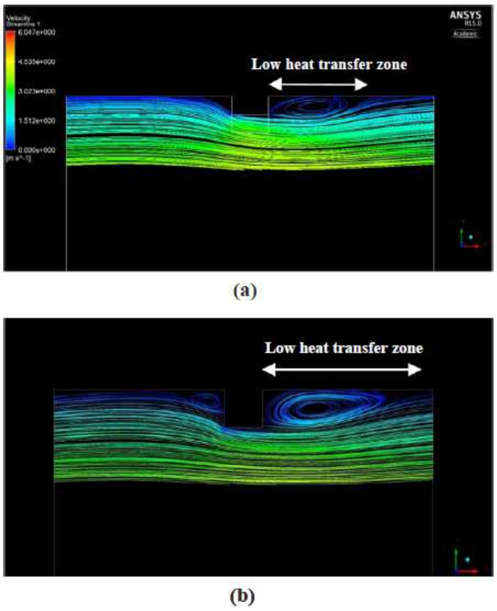

Figure 4: Streamline Plots of Velocity Showing the Recirculation Zones Upstream of (a) Square Wavy Profiled Ribs and (b) Transverse Square Ribs(Singh and Singh, 2018)

This is evidenced in Figure 4 (Singh and Singh, 2018) which shows a relatively smaller recirculation zone on the upstream side of square wave profiled ribs as compared to the transverse square ribs. The results show that the Nusselt number enhancement is more for square wave profiled ribs for the entire range of flow rates considered in their analysis. The maximum thermal enhancement factor was reported as 1.43 as against 1.39 for transverse square ribs. They have also shown that the effective thermal performance of square wave profile ribs are superior to tranvserse circular ribs (Gupta et al, 1993), transverse fins (Mahmood et al, 2015), fins and baffles (Mohammadi and Sabzpooshani, 2013) within the flow rates used in the analysis. A new concept of tapered ribs as shown in Figure 5was reported by Gupta and Varshney (2017) in which theystudied the effect of tapered rib parameters on the thermal performance of air heater. The taper angle was varied as 1.6^o, 2.3^o and 3.2^o while the pitch was selected as 10, 15, 20 and 25 mm. The relative height was varied from 0.042 to 0.084. The optimum value of thermal enhancement factor was reported to be 1.91 for the taper angle of 1.6^o and a

relative pitch value of 10.7 for the flow Reynolds number of 12,000. The CFD results revealed that the edges of tapered ribs produce secondary flows and greater mixing of fluids at the centre of ribs which enhance heat transfer as compared to rectangular sectioned ribs. They concluded that the tapered ribs generate more inconsistency in the flow and hence a relatively higher turbulent kinetic energy which leads to higher heat transfer as shown in Figure 6.

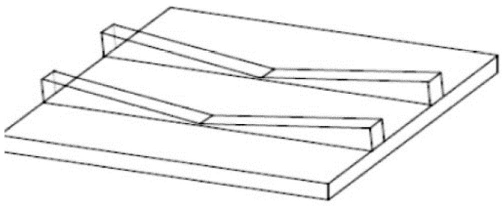

Figure 5: Geometry of Tapered Ribs on the Absorber Plate (Gupta and Varshney, 2017)

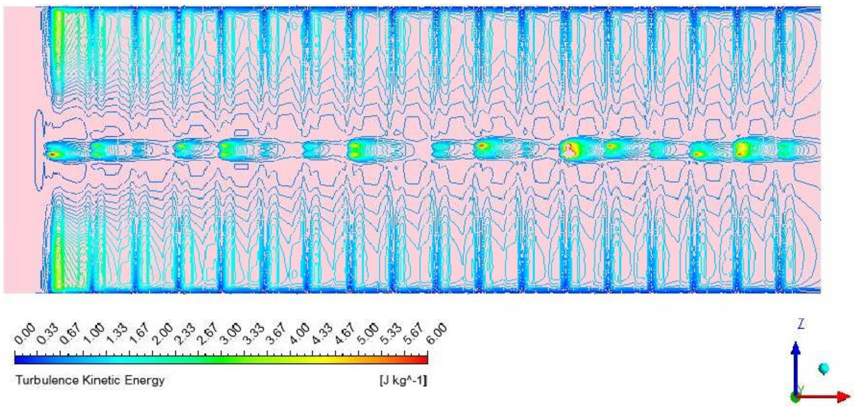

Figure 6: Contour Plot of Turbulent Kinetic Energy (Gupta and Varshney, 2017)

Kumar et al. (2017)numerically evaluated the effect of rectangular ribs in a triangular sectioned duct solar air heater. The duct apex angle of the triangular duct was maintained at 60^o. The inlet section, test section and exit section were fixed at 350 mm, 300 mm and 180 mm respectively. The normalised pitch was selected within 5 and 15 while the relative rib height was selectedwithin 0.25 and 0.04. They introduced a new roughness parameter called rib aspect ratio and was varied between 0.25 and 4. The CFD results reveal that the ribs should be placed in such a distance that the reattachment points occur just behind the successive ribs so as to have maximum number of reattachment points which leads to greater heat transfer. They concluded that the highest thermal enhancement factor was about 1.89 for the relative roughness pitch of 10, relative rib height of 0.04 and relative aspect ratio of 4. Chaube et al. (2006) conducted a comparative two dimensional CFD analysis to evaluate the efficacy of rectangular rib of 2 mm x 3 mm size, square rib of 3 mm x 3 mm size, chamfered rib with a chamfer angle of 11^o, 13^o, and 15^o, semi-circular rib of 3mm diameter and circular rib of 3 mm diameter for the Reynolds number range of 3000 to 20,000. They made use of SST k-w turbulence model upon validating the variation of Nusselt number in the inter-rib regions against the experimental results of Tanda (2004). The analysis showed that the highest heat transfer was obtained for rectangular rib configuration.

2.2 Investigations on Inclined Ribs

Thakur et al (2017) determined the effect of inclined hyperbolic ribs on the overall thermal performance. The ribs were arranged in the form of simple inclined ribs, V-shaped ribs and W-shaped ribs and the inclination of rib for each arrangement was varied from 30^o to 60^o. The roughness height and pitch were fixed at 1.0 mm and 10 mm respectively. They conducted a three dimensional CFD analysis using RNG k-e turbulence model. They found that the inclination of ribs generated non-stagnant secondary flows as shown in Figure 7 which enhances heat transfer. Of all the configuration considered in the analysis, the V-shaped ribs with 60^o inclination were found to produce the best thermo-hydraulic performance.

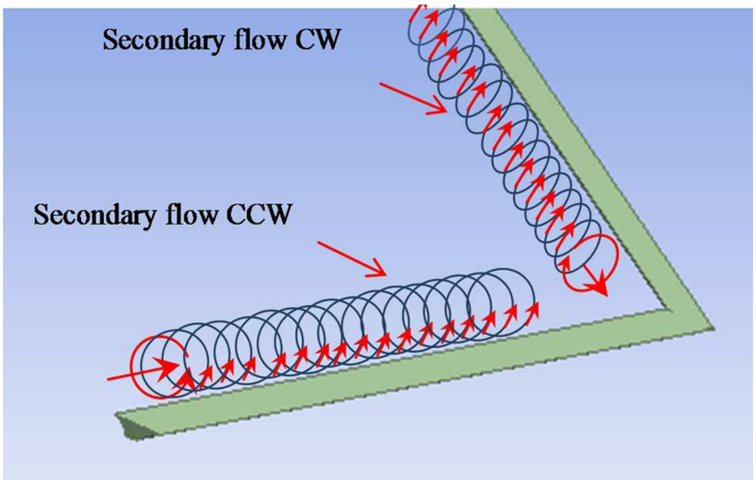

Figure 7: Non-Stagnant Secondary Flows Due to Inclined Ribs (Thakur et al, 2017)

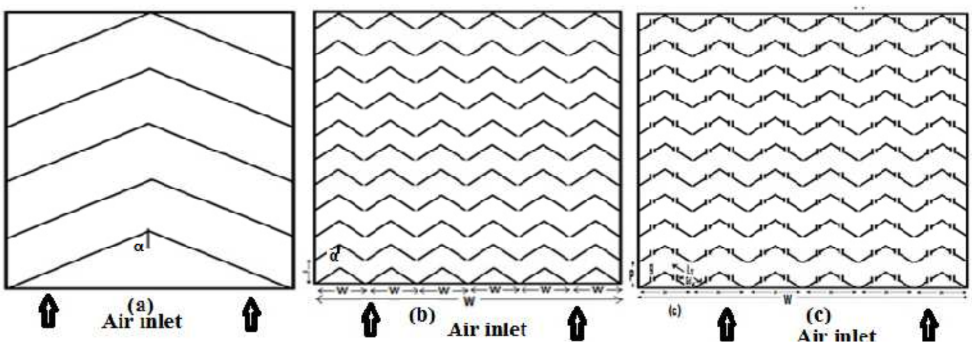

Figure 8: Geometry of (a) V-Shaped Ribs (b) Multi V-Shaped Ribs and (c) Multi V-Shaped Ribs with Gap (Anil Kumar, 2014)

Anil kumar (2014) compared the performance of V-shaped ribs, Multi v-shaped ribs and Multi v-shaped ribs with gap using three dimensional CFD analysis. The geometry considered for the analysis is shown in Figure 8. The range of parameters considered for V-ribs were $P/e=10$, $e/D=0.043$ and $\alpha=60°$ while the parameters for Multi V-shaped ribs were $W/w=6$, $P/e=10$, $e/D=0.043$ and $\alpha=60°$. The parameters for Multi-V-shaped rib with gaps were $W/w=6$, $P/e=10$, $e/D=0.043$, $\alpha=60°$, $g/e=1.0$ and $Gd/Lv=0.69$.

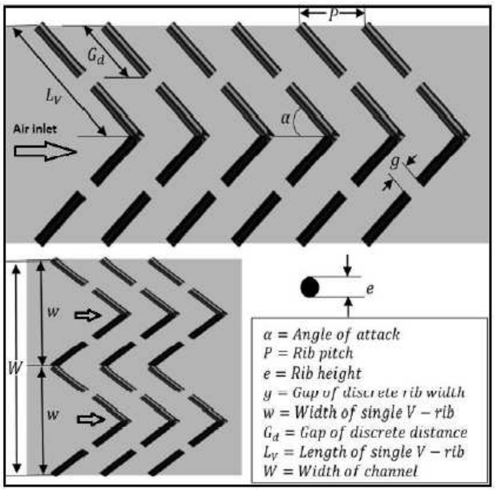

Figure 9: Discretely Placed Multi V-Shaped Rib on the Absorber Plate (Kumar and Kim, 2016a)

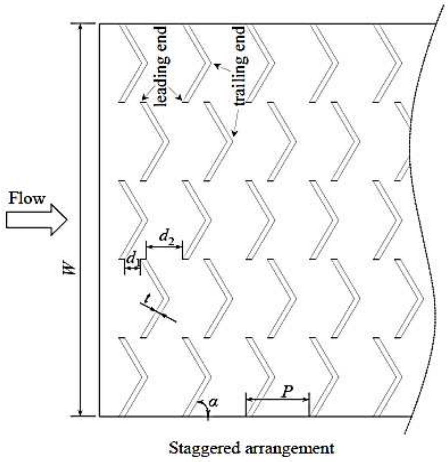

Figure 10: Staggered V-Shaped Ribs (Kumar and Kim, 2016a)

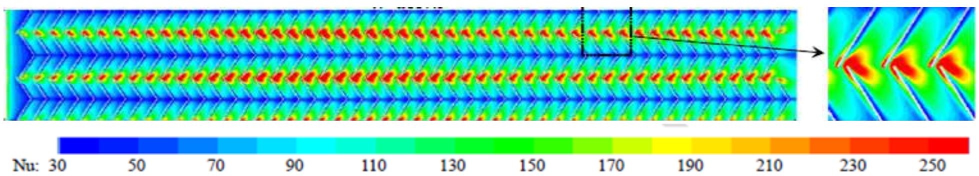

Figure 11: Nusselt Number Distribution over Staggered V-Shaped Ribs (Zin et al, 2017)

They concluded that the Multi-V-shaped rib with gaps provides increased heat transfer among the three configurations. Kumar and Kim (2016a)numerically evaluated the effectiveness of discretely placed Multi V-shaped ribs as shown in Figure 9. The relative discrete distance, relative rib height, relative pitch, relative width and flow attack angle were fixed at 0.69, 0.043, 10, 6.0 and 60^{o} respectively. The CFD results revealed that the discretely placed Multi V-ribs produced mixing of secondary flows with the main flow thereby increasing the turbulence levels and hence heat transfer. They also evaluated the effect of discrete V-shaped rib with staggered rib as well as dimple staggered rib with the enhancement of thermo-hydraulic performance parameter varying between 2.74 and 3.82.

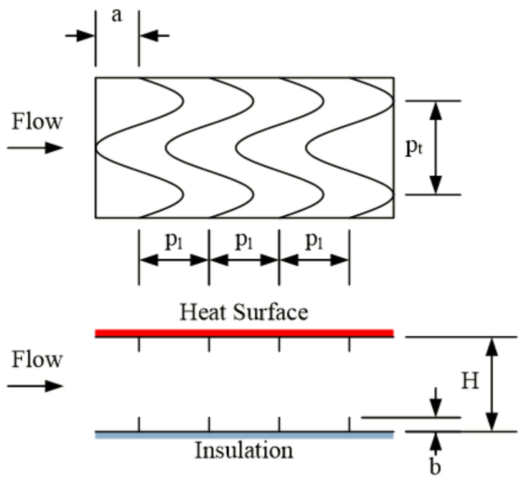

Figure 12: Wavy Baffles on the Absorber Plate (Promvonge et al, 2014)

Zin et al (2017) have shown that placing the V-shaped ribs in a staggered arrangement as shown in Figure 11 could significantly enhance the Nusselt number by about 26% as compared to inline arrangement. Figure 10 clearly shows augmented Nusselt number due to enhanced fluid mixing in the inter-rib region. The thermo-hydraulic performance was found to increase by 18% as compared to inline arrangement. Sriromreun et al (2012) evaluated the effect of z-shaped baffles with an angle of attack of 40^o on the thermo-hydraulic performance of solar air heater. The Z-baffles were found to create co-rotating vortices which enhance the turbulence intensity in the inter-rib region and hence the heat transfer. The influence of wavy baffles was investigated by Promvonge et al (2014) using three dimensional CFD analysis as shown in Figure 12. They have reported a maximum Nusselt number enhancement of about 1.66 times as compared to the smooth duct. The heat transfer augmentation was due to the wavy baffle induced flow impingement and reattachment. The baffles were found to produce longitudinal vortex flows which augment the heat transfer.

2.3 Investigations Involving Novel Methods of Turbulence Enhancement

A novel method of helical channelling of air flow in the solar air heater was reported by Heydari and Mesgarpour (2018) as shown in Figure 13. A triangular channel was designed in such a way that the air flows in a helical path absorbing heat from the top and bottom surface of the absorber plate. A three dimensional CFD analysis was carried out to determine the flow and heat transfer characteristics. The CFD results revealed the formation of vortices at the turning points of the helical path which resulted in enhanced fluid mixing as well as higher pressure drop. The results showed that the thermal efficiency is about 14.7% higher than the smooth duct and about 8.6% higher than the double pass solar air heater with fins for the same flow rate conditions. Manjunath et al (2018) have shown that the sinusoidal corrugations on the absorber plate as shown in Figure 14 could provide significant flow disturbances which leads to higher levels of turbulence intensity. They conducted a three dimensional CFD analysis using discrete ordinates radiation model and SST k-w turbulence model. The non-dimensionallength of corrugation wave was varied between 1.0 and 6.0 while the non-dimensional corrugation amplitude was selected between 1.5 and 4.0. The average enhancement in thermal efficiency was found to be about 12.5% as compared to smooth duct. The effective efficiency was found to be higher only at lower flow rate conditions. Karanth et al (2013) evaluated the effect of corrugations of different geometries such as V-corrugation, sinewave corrugation, arched corrugation and W-shaped corrugations on the absorber plate as shown in Figure 15. The analysis showed that the V-shaped corrugation provide higher heat transfer enhancement at higher flow rate conditions

while the sinewave corrugations were found to be effective at lower flow rate values. The W-corrugations performed the lowest among all the corrugation geometries considered in the analysis.

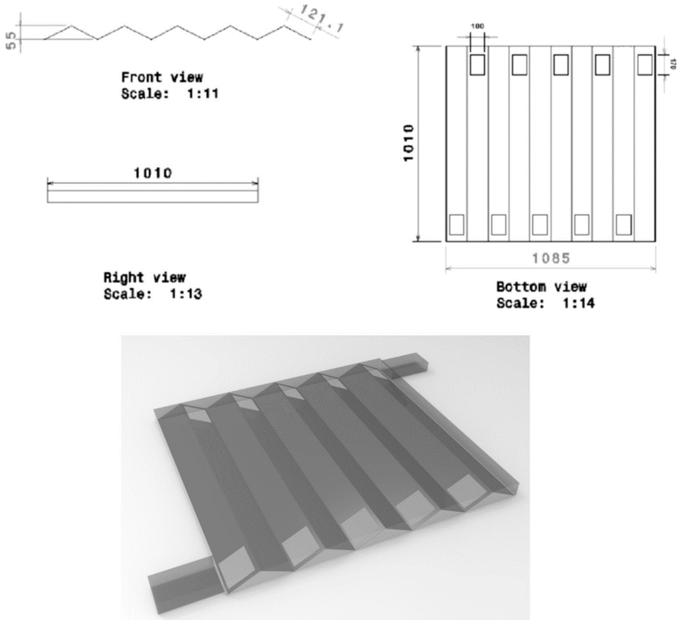

Figure 13: Helical Channelling of Absorber Plate (Heydari and Mesgarpour, 2018)

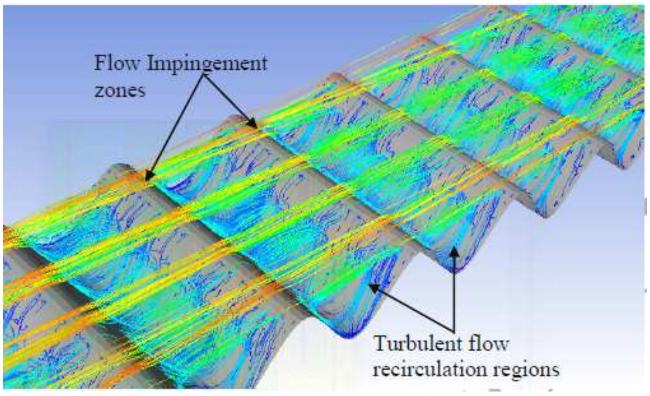

Figure 14: Turbulent Mixing Zones due to Sinewave Corrugations Ion Absorber Plate (Manjunath et al, 2018)

Manjunath et al (2017) made use of a novel spherical turbulence generator on the absorber plate. Spheres of diameters such as 5,10,15,20 and 25mm for a relative pitch value of 3, 6 and 12 were investigated for effective efficiency enhancement in the flow rate range corresponding to the Reynolds number range of 4000 to 24,000. The three dimensional CFD analysis revealed that the spheres provided intense turbulent mixing of fluid around the spheres thereby augmenting the heat transfer. The thermal efficiency was found to increase to a maximum extent of abpout 23.4% relative to the smooth duct. A novel design of conical ribs was reported by Alam and Kim (2017) using which they evaluated the performance in terms of thermal efficiency and thermal enhancement factor. The relative pitch was varied between 6.0 and 12 while the relative height of the ribs were varied between 0.02 and 0.044. The best thermal efficiency was reported as 6938% while the effective performance parameter was found to be 1.346. Handoyo et al (2016) made use of delta-shaped obstacles in a V-corrugated channel of solar air heater.

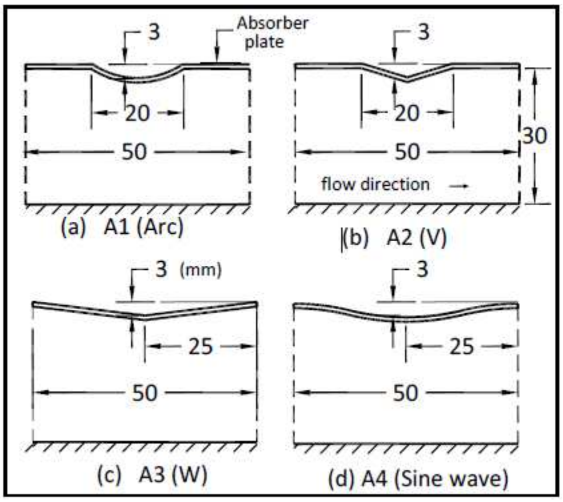

Figure 15: Various Corrugation Geometries on Absorber Plate (Karanth et al, 2013)

The obstacles were found to create flow separation and swirl flow in the immediate downstream thereby enhancing the turbulence levels and heat transfer. The Nusselt number was found to increase by 3.46 times while the friction factor increased by 19.9 times as compared to the smooth duct. It was also found that the optimal spacing of obstacles is equal to its height. Kumar and Kim (2016b) have compared the thermal performance of obstacles such as V-shaped baffle, multi-V-shaped perforated baffle, continuous V-down baffle, rib groove baffle, single V-down baffle, Z-shaped baffle, winglet vortex generator, delta shaped baffle, U-shaped baffle and transverse perforated baffle for the flow Reynolds number range of 3000 to 10000. They concluded that the Multi-V-shaped perforated baffles produce the best thermal enhancement factor among the various configurations of baffles published in the literature.

3. CONCLUSIONS

A detailed review of the CFD investigations on turbulence enhancement in solar air heater for improvement in thermal performance is presented in this paper. The major conclusions of the review work are as follows:

- The CFD analysis have been shown to produce results that have good agreement with experiments and analytical correlations. As a result, CFD simulation studies pave way for seeking parametric analysis in a relatively quick time and effort.
- The CFD results have revealed the complex flow patterns in the air flow in the presence of turbulence enhancement elements which helps to establish the flow characteristics and design efficient solar air heater systems.
- The turbulence models such as RNG k-e, SST k-w and Realizable k-e models have been shown to capture the turbulence characteristics of air flow in a solar air heater that are in close agreement with experiments.
- Artificial roughness elements, corrugations, baffle plates and vortex generators on the absorber plate are the adopted methods for turbulence enhancement in solar air heater systems. Artificial roughness elements also called turbulators are the most widely used method.
- Analysis involving transverse ribs are carried out using two dimensional computational domain due to the absence of secondary flows and the results have been shown to be in close agreement with experiments.

- Analysis involving inclined ribs, corrugations and vortex generators have been done using three dimensional computational domain in order to capture the secondary flow which significantly influence the thermal performance.
- The thermal performance of multi-V-shaped perforated baffle has been reported to be superior to designs such as V-shaped baffle, continuous V-down baffle, rib groove baffle, single V-down baffle, Z-shaped baffle, winglet vortex generator, delta shaped baffle, U-shaped baffle and transverse perforated baffle for the flow Reynolds number range of 3,000 to 10,000.
- The inclined ribs have been reported to produce greater enhancement in the Nusselt number as well as friction factor. This is due to the formation of secondary flow vortices which interact with the main flow which enhance the flow turbulence levels.
- Novel methods of turbulence enhancement such as spherical turbulence generators, winglet and delta shaped vortex generators, sinewave corrugations have been investigated using CFD simulation which revealed the complex flow patterns of air flow and its influence on thermal performance.
- Experimental investigations have been reported on a number of configurations of turbulence enhancement element. On the contrary, it is observed that there have been a relatively lesser number of CFD simulation studies, most likely due to the challenges in meshing and higher computational requirements with increasing complexity of design.
- Not much CFD simulation studies have been reported on the use of triangular duct solar air heater fitted with artificial roughness elements. More simulation studies using different roughness geometries and arrangement could help bring out the optimal performance levels of triangular duct solar air heater.
- Most of the simulation studies consider constant heat flux of 1000 W/m^2 on the absorber plate. However, the solar load model feature of the software tool could be made use of to provide simulated solar insolation on the absorber plate for a given day, time and location to determine the performance of the collector at different times of the day.
- The performance of tapered transverse ribs could be investigated further for the different geometrical cross-section.
- Numerical simulation studies involving double pass arrangement has not been reported in the literature and needs to be explored numerically.

4. ACKNOWLEDGEMENTS

Authors are greatful to the School of Engineering and IT, MAHE Dubai campus and Department of Mechanical and Manufacturing Engineering, Manipal Institute of Technology, Manipal, India for providing the necessary facilities to carry out this study.

REFERENCES

1. Yadav, A. S., & Bhagoria, J. L. (2014a). A numerical investigation of square sectioned transverse rib roughened solar air heater. International Journal of Thermal Sciences, 79, 111–131.

2. Yadav, A. S., & Bhagoria, J. L. (2014b). A numerical investigation of turbulent flows through an artificially roughened solar air heater. Numerical Heat Transfer; Part A: Applications, 65(7), 679–698.

3. Ahn, S. W. (2001). The effects of roughness types on friction factors and heat transfer in roughened rectangular duct. International Communications in Heat and Mass Transfer, 28(7), 933–942.

4. Singh, I., & Singh, S. (2018). CFD analysis of solar air heater duct having square wave profiled transverse ribs as roughness elements. Solar Energy, 162(July 2017), 442–453.

5. Gupta, D., Solanki, S. C., & Saini, J. S. (1993). Heat and fluid flow in rectangular solar air heater ducts having transverse rib roughness on absorber plates, 51(1), 31–37.

6. Mahmood, A. J., Aldabbagh, L. B. Y., & Egelioglu, F. (2015). Investigation of single and double pass solar air heater with transverse fins and a package wire mesh layer. Energy Conversion and Management, 89, 599–607. doi:10.1016/j.enconman.2014.10.028.

7. Mohammadi, K., & Sabzpooshani, M. (2013). Comprehensive performance evaluation and parametric studies of single pass solar air heater with fins and baffles attached over the absorber plate. Energy, 57, 741–750.

8. Gupta, A. D., & Varshney, L. (2017). Performance prediction for solar air heater having rectangular sectioned tapered rib roughness using CFD. Thermal Science and Engineering Progress, 4, 122–132.

9. Kumar, R., Kumar, A., & Goel, V. (2017). A parametric analysis of rectangular rib roughened triangular duct solar air heater using computational fluid dynamics. Solar Energy, 157(August), 1095–1107.

10. Chaube, A., Sahoo, P. K., & Solanki, S. C. (2006). Analysis of heat transfer augmentation and flow characteristics due to rib roughness over absorber plate of a solar air heater. Renewable Energy, 31(3), 317–331.

11. Rasheed, W., Ahmed, S., & Ghyadh, N. (2016). Investigation Potential Flow About Curved Wing Using Panel Method. International Journal of Mechanical and Production Engineering Research and Development (IJMPERD) ISSN (P), 2249-6890.

12. Tanda, G. (2004). Heat transfer in rectangular channels with transverse and V-shaped broken ribs. International Journal of Heat and Mass Transfer, 47(2), 229–243.

13. Thakur, D. S., Khan, M. K., & Pathak, M. (2017b). Solar air heater with hyperbolic ribs: 3D simulation with experimental validation. Renewable Energy, 113, 357–368.

14. Kumar, A. (2014). Analysis of heat transfer and fluid flow in different shaped roughness elements on the absorber plate solar air heater duct. Energy Procedia, 57, 2102–2111.

15. Kumar, A., & Kim, M.-H. (2016a). CFD Analysis on the Thermal Hydraulic Performance of an SAH Duct with Multi V-Shape Roughened Ribs. Energies, 9(6), 415.

16. Jin, D., Zuo, J., Quan, S., Xu, S., & Gao, H. (2017). Thermohydraulic performance of solar air heater with staggered multiple V-shaped ribs on the absorber plate. Energy, 127, 68–77.

17. Sriromreun, P., Thianpong, C., & Promvonge, P. (2012). Experimental and numerical study on heat transfer enhancement in a channel with Z-shaped baffles. International Communications in Heat and Mass Transfer, 39(7), 945–952.

18. *Promvonge, P., Noothong, W., & Thianpong, C. (2014). Numerical heat transfer investigation in solar air heater channel with Wavy-Baffles. Advanced Materials Research, 1051, 808–812.*

19. *Heydari, A., & Mesgarpour, M. (2018). Experimental analysis and numerical modeling of solar air heater with helical flow path. Solar Energy, 162(November 2017), 278–288.*

20. *Kumar, R., Pedgopu, V., Kumar, A. N. I. L., Thakur, R. O. B. I. N., & Pundir, A. N. I. L. (2013). CFD based analysis heat transfer and friction characteristics of broken multiple rib roughened solar air heater duct. Int J Mech Prod Eng Res Dev, 3, 165-172.*

21. *Manjunath, M. S., Karanth, K. V., & Sharma, N. Y. (2018). Numerical investigation on heat transfer enhancement of solar air heater using sinusoidal corrugations on absorber plate. International Journal of Mechanical Sciences, 138–139, 219–228.*

22. *Vasudeva Karanth, K., Manjunath, M. S., & Yagnesh Sharma, N. (2013). Three dimensional CFD analysis of solar air heater for enhancement of thermal performance using surface corrugation. International Journal of Earth Sciences and Engineering, 6(4), 2–6.*

23. *Alam, T., & Kim, M. H. (2017). Heat transfer enhancement in solar air heater duct with conical protrusion roughness ribs. Applied Thermal Engineering, 126, 458–469.*

24. *Handoyo, E. A., Ichsani, D., Prabowo, & Sutardi. (2016). Numerical studies on the effect of delta-shaped obstacles' spacing on the heat transfer and pressure drop in v-corrugated channel of solar air heater. Solar Energy, 131, 47–60.*

25. *Kumar, A., & Kim, M.H. (2016b). Thermal Hydraulic Performance in a Solar Air Heater Channel with Multi V-Type Perforated Baffles. Energies, 9(7), 564.*